The State of LIGA Development

Jill Hruby
Sandia National Laboratories
Livermore, CA

Biography:
Jill Hruby is Program Manager for Microsystems Technology and Deputy Director of the Materials and Engineering Sciences Center at Sandia National Laboratories in Livermore California. Jill has managed the LIGA project at Sandia since its inception in 1992. Jill also serves as the chair of the West Coast LIGA Group. Other activities managed by Jill include microfluidics, thick UV resist lithography, and other high aspect ratio microtechnologies efforts. Jill joined Sandia in 1983 after completing her MSME at University of California at Berkeley, and her BSME at Purdue University. In addition to microsystems technology, Jill has been involved in solar energy, weapons component development, and materials science research at Sandia.

Abstract:
The LIGA program at Sandia has developed baseline processes for producing metal microparts, and has continuing research and development to decrease the cost, expand the materials suite, and explore novel three-dimensional processing approaches. Sandia has been working with various commercial companies to produce prototype parts. One commercial partner and one captive DOE production plant has begun the establishment of LIGA production capabilities based on Sandia's prototyping work.

In this paper, the challenges associated with establishing LIGA fabrication and production capabilities will be addressed. In addition, Sandia's research results in materials availability and three-dimensional processing will be shown. These research efforts are aimed at lowering the cost and increasing the flexibility of LIGA in the future.

Introduction:
The first publications describing the LIGA process appeared in the mid-1980s [1]. Since that time, there has been a considerable investment in many countries, especially Germany, in maturing LIGA technology for commercialization. These efforts have resulted in several commercial products, perhaps most notably a spectrometer [2], an aspirator [3], and a miniature motor [4]. These products, and others, combine LIGA with different microfabrication techniques to produce a final product that can be manufactured in a cost-effective manner. These products also generally rely on replication technologies to decrease the cost of the LIGA-produced elements.

Overall, the commercialization of LIGA has been slow and a "killer application" has yet to emerge in the commercial sector. At the same time, there has been dialog in the MEMS community about whether LIGA will find a few primary ("killer") applications or if it will become a pervasive, high-end machining technology more akin to wire electrodischarge machining (EDM). In the "killer application" market, it is expected that dedicated LIGA foundries would be owned and operated by the companies that sell the final product. In the case of a pervasive market, LIGA foundries could be suppliers, and these foundries may well supply MEMS technologies other than LIGA. Alternatively, dedicated beam lines with matched mask technologies, could be operated for a larger number of down-stream processing facilities. Of course, some combination may emerge where dedicated LIGA fabrication serves a single company or single market purpose, and excess capacity serves other smaller applications. Many believe the promise that LIGA holds must be commercially realized in the next few years or it will never happen.

In this paper, the facilities required for a full service LIGA capability are described based on the work at Sandia. In addition, the challenges associated with moving from prototyping to production will be discussed. Finally, some exciting technical developments that may lower the cost of LIGA and technologies that allow more complex geometries are described. These types of breakthroughs may be necessary before wide spread acceptance of LIGA for mass production.

Required LIGA Facilities and Equipment:

LIGA, like other microfabrciation technologies, requires a number of serial processes in order to produce a finished product. In the instance when a metal micropart or microtool is the desired product, the following minimum process steps are required:

- CAD drawing and LIGA mask layout
- Chrome mask fabrication
- LIGA mask fabrication
- Substrate and/or photoresist preparation
- X-ray synchrotron exposure
- Photoresist development
- Electroplating
- Planarization

More detailed descriptions of the LIGA process steps can be found in the literature [5].

These process steps require cleanroom facilities, specialized equipment, and access to a synchrotron, none of which is readily available to most commercial entities, especially those not already in the MEMS business. However, the availability of all is beginning to increase.

Available LIGA Facilities and Equipment:

Unlike silicon surface micromachining, LIGA did not emerge from an already commercially developed process. Because of this, a supplier base for LIGA tools does not exist. Further compounding this issue, LIGA requires the use of a x-ray synchrotron. The current availability of equipment and U.S. synchrotron access is briefly reviewed here.

Equipment: With the exception of a x-ray scanner developed by Jenoptik [6], no commercial equipment has been developed for the purpose of being LIGA tools. However, for a number of steps in the LIGA process, it is easy to find available hardware or software to accomplish the job. A quick review of the equipment is provided here.

Any number of commercial CAD programs can be used for drawing the LIGA parts and laying out the mask. At Sandia, we commonly use AutoCAD 2000 from Autodesk.

Similarly, tools to produce chrome masks are readily available because they are common to the integrated circuit market. At Sandia, we prefer to procure the chrome masks rather than buying and maintaining the capital equipment needed for in-house fabrication. Chrome mask suppliers capable of making the appropriate geometries for LIGA are relatively easy to locate.

Currently, there are many different types of LIGA masks used, mostly due to the different energy spectra and flux at the various synchrotrons. Some of these masks rely on thin membranes and others on thicker substrates to support the absorber. Most, but not all, use electroplated gold as the x-ray absorption material. Regardless of the mask technology, the equipment needed to make the LIGA mask is commercially available, although the primary applications for the equipment is UV lithography, not LIGA masks. At this time, it is generally the decision of the LIGA fabricators to choose a mask technology and develop the appropriate processes. Sandia has licensed the know-how to make LIGA masks on a non-exclusive basis and this is an option for commercial entities to quickly develop LIGA mask fabrication capability.

The x-ray photoresist most widely used in LIGA is polymethylmethacralate, PMMA, and is commercially available. The long-term availability of the high molecular weight PMMA needed for LIGA is under review by Sandia and a few other research groups at this time, and it may be necessary to develop additional suppliers. It is anticipated that suppliers for PMMA can be found.

Typically the PMMA must be adhered to a metal base or metallized substrate either before exposure or before development. This must be done for complex geometries that would fall apart during development without adhesion. In any case, before electroplating, a metal substrate must be adhered to the developed PMMA to serve as a plating seed layer. The adhesion of the PMMA to the substrate is a critical process and there is patented technology, as well as know how, required for this part of the LIGA process.

As mentioned earlier, there is a commercially available scanner for use at a synchrotron. In addition, most synchrotrons with LIGA lines have a scanner already installed. Generally, a scanner is required for at least vertical translation. For production purposes it may be desirable to have multiple sample mounts to take advantage of 24 hours of light without around the clock staffing. For R&D purposes, it is sometimes desirable to have capabilities other than just vertical scan, for example, rotation may be of interest.

The two most difficult processes for tools are development and electroplating. Both of these process steps are difficult and can be quite time consuming, depending on geometries. Commercially available tools do not exist for LIGA and they can not be borrowed from related technologies. At Sandia, we have designed and built custom LIGA development and plating stations. This would also be required for production at this time.

Lastly, the equipment for planarization can be purchased commercially, although modifications may be necessary to use the equipment for LIGA. At Sandia, we have modified commercially available lapping and grinding equipment.

Synchrotrons: For commercial users, many believe the most difficult issue is synchrotron source availability. While the cost of building a synchrotron is indeed very high, it is also true that many synchrotrons currently exist that are useful for LIGA. A quick review of LIGA lines at existing synchrotrons is provided here.

There are many synchrotron development activities for LIGA worldwide. LIGA research groups utilize synchrotrons in Germany, Taiwan, United Kingdom, France, Japan, United States, and other countries. The largest synchrotron development activity at this time is in Germany, where a new synchrotron is being constructed specifically for x-ray lithography [7].

In the U.S., most existing synchrotrons now have LIGA beam lines. The two beam lines primarily used by Sandia are: (1) a dedicated LIGA line at the Stanford Synchrotron Radiation Laboratory (SSRL), and (2) a dedicated LIGA line at the Advanced Light Source (ALS) and Lawrence Berkeley National Laboratory (LBNL). Both of these beam lines are operated by participating research teams. At SSRL the beam line is operated by Sandia and the NASA Jet Propulsion Laboratory (JPL). At ALS the beam line is operated by Sandia, JPL, and LBNL. In addition to these two synchrotron lines, there are two additional DOE synchrotrons that are used for LIGA. Brookhaven National Laboratory has two dedicated beam lines for LIGA. One of these lines is to support LIGA R&D, the other is for LIGA production. Brookhaven has established a program that allows industrial users to pay for beam time in order to produce commercial product. No investment in infrastructure is necessary to use the Brookhaven lines. Argonne National Lab has also conducted LIGA exposures, but does not have a beam line used independently by other research or industrial users. Two other U.S. beam lines are active in LIGA, CAMD at Louisiana State University [8] and Aladdin [9] at University of Wisconsin. CAMD offers an exposure service as well as synchrotron access if desired.

Given the synchrotron status, commercially interested LIGA producers have several options. They can pay for beam time at an existing beam line at Brookhaven or CAMD, or they can develop a dedicated beam line at one of the other synchrotrons. Both ALS and SSRL (and perhaps others) are willing to consider commercial use of beam lines, and it is anticipated that a dedicated single-company commercial beam line for LIGA will exist at ALS within the next year. The cost of building a dedicated beam line for LIGA is between about $200K and $600K, and at this time is probably not as big of a hurdle as perceived by many industrial entities.

Prototyping to Production Barriers:
In addition to the availability of beam lines and equipment for LIGA, there are a few other prototype to production barriers. They include cost, throughput, process reliability, product reliability, and assembly and packaging. Naturally, these issues are not independent.

Cost, Throughput, and Process Reliability:
The cost of metal LIGA product produced using standard LIGA processes is high. These products can be introduced into the market place only for high value applications. At Sandia, the cost of producing a standard 3- or 4-inch diameter LIGA wafer is approximately $10K. However, if the LIGA wafer is used as a metal tool to produce replicate parts, the cost of the final product can be lowered substantially. These products potentially could be introduced in the commodity market.

Throughput is one of the issues driving both the cost and the total number of products that can be produced without significant investments in new synchrotron sources. Again, throughput is much less of an issue if replication technologies are utilized to produce the final product. Nonetheless, throughput is an issue in the overall productivity of LIGA synchrotron lines and process facilities. In order to fully consider throughput issues, many complex cost-of-ownership issues must be addressed. Optimization studies include the combined time to complete the exposure plus development steps [10], and selection of mask and/or photoresist technology [11]. As an example, the areal throughput for exposure as a function of resist thickness and mask technology is shown in Figure 1. In this Figure a large increase in areal throughput results when a thin membrane mask is used instead of a mask with a 100 micron thick silicon substrate. This increase in areal throughput must be weighed against other issues like mask cost and robustness before an optimum for any specific production capability can be established. At Sandia, we typically choose the silicon substrate mask for R&D because the mask cost is substantially lower than the membrane mask, and synchrotron time is not a limiting factor. Other considerations include optimum utilization of the 24-hour synchrotron source availability with only one shift of personnel.

Process reliability remains an issue in LIGA, since experience with full-scale production is not available. Information on process reliability will hopefully be gained from the adoption of ISO 9000 standards at Forschungszentrum Karlsruhe GmbH. Process reliability may in fact be simpler in production than in R&D, but issues such as how long an electroplating bath can be used before being replaced, will always need to be considered. At Sandia, we continuously filter our electroplating and development baths in an attempt to keep high quality and long useful lives.

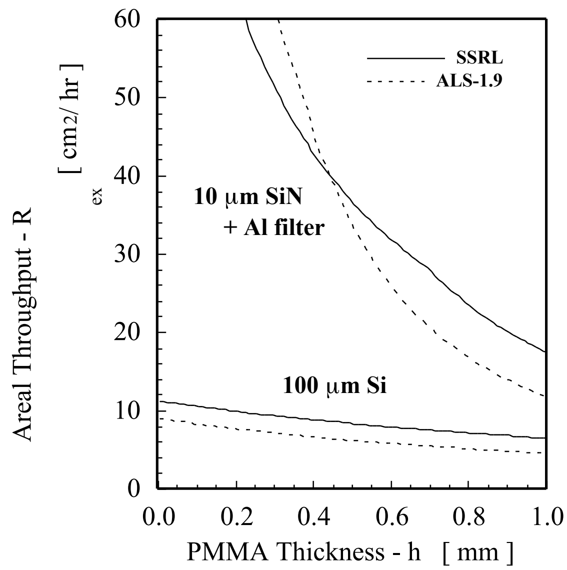

Figure 1. Areal exposure throughput for SSRL and ALS sources using a 100 μm silicon mask substrate and a membrane substrate with aluminum filter to limit through-thickness dose variation. Minimum dose is 4 kJ/cm^3; maximum permitted dose is 16 kJ/cm^3. Optimum mask substrate can increase throughput by a factor of three or more.

Product Reliability and Assembly and Packaging: Product reliability and assembly and packaging have repeatedly been cited as the primary barriers to application of MEMS. LIGA is no exception.

Product reliability usually relies on extensive testing. There are several barriers to overcome in product testing for LIGA. One is the required time and two is the availability of test equipment.

In the markets most attractive for MEMS, commercial product is introduced rapidly to have a competitive edge. Reliability is often established in part on previous experience with like products. In the case of LIGA and

MEMS, there are not many like products or data for comparison. Therefore, the time required to collect and interpret data, and make reliability assessments, can be long and therefore become a barrier to market introduction.

The time to collect and interpret reliability data is even more difficult because the tests are not necessarily simple to conduct. Test equipment for these small structures, with combined mechanical and electrical functions, can be a challenge to design and is not readily available.

LIGA is a method to produce precise, usually small, piece parts that need to be assembled into an assembly. The assembly process for small parts is also a developing field with no standard commercial technologies available. At Sandia, most LIGA parts are currently assembled by hand, with some R&D in robotic manipulation [12].

Finally, packaging of LIGA assemblies must be completed prior to most applications. Packaging issues may include joining, sealing, vibration isolation, and more. Each of these areas is still accomplished on a case-by-case basis, with no standards and very few reported results. Sandia is initiating activities to look at the importance of lifetime issues such as common oxide growth and capillary condensation to the overall packaging concerns.

Despite the lack of detailed information such as reliability and packaging, LIGA products are still making it to the market. It is anticipated that at least one LIGA commercial product will be introduced in the U.S. in the next year. The precise, high aspect ratio features are superior to those fabricated using other approaches and individual issues are being addressed on a case by case basis. As these issues get addressed more generally and in more detail, we can anticipate an increase in the number of LIGA products that are commercialized.

Technology Advances

Research currently being pursued at Sandia addresses some of the issues in achieving cost-effective production of LIGA. Two areas will be discussed briefly here: metallic replication from LIGA masters, and contour polishing using a LIGA tool.

Metallic Replication: Replicating a LIGA metal master in plastic has been reported using both hot embossing [13] and injection molding [14]. However, replicating LIGA structures in metal has not been as successful. There are several approaches to replication including plunge EDM. Sandia's most recent R&D activity in metallic replication uses metallic nanoparticles. The process steps are:

- fabricate LIGA metal master mold
- replicate LIGA master in polymer using injection compression molding
- make slurry of metal nanoparticles and binder
- press nanoparticle slurry into injection molded replicate
- sinter and release

Figure 2 shows an SEM image of a stainless steel micropart made using this replication approach. The primary issues requiring additional R&D include shrinkage minimization/control during sintering and density of the final part. However, such an approach, if successful, could provide metal microparts in a very cost-effective manner. Injection compression replication is able to produce hundreds of replicates an hour with little wear of the master LIGA tool.

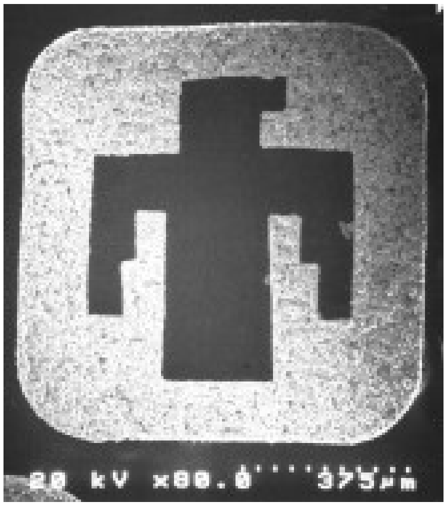

Figure 2. A stainless steel micropart made using a LIGA tool, replicating the tool in polymer by injection compression molding, filling the polymer replicate with stainless steel nanoparticles, and sintering.

Contour Polishing: At Sandia, we have been approached by a number of commercial entities interested in the fabrication of devices with smooth interior diameters of various dimensions, as shown in Figure 3. Our first approach to this problem was to build a number of LIGA "washers" (wire EDM parts were too rough) and sandwich them together to form the final product. This approach required many LIGA runs, a joining technology, and an alignment scheme. The tediousness of using this approach inspired a new idea using LIGA as a tool instead of the final product.

The new approach, shown schematically in Figure 4, relies on creating a metal LIGA part that has the two dimensional shape of the interior diameter. This tool is then used to polish a rod of PMMA to the desired geometry. The rod is then seeded with metal, electroplated, and the PMMA dissolved. The final product is a metal tube with a complex internal diameter of very smooth metal.

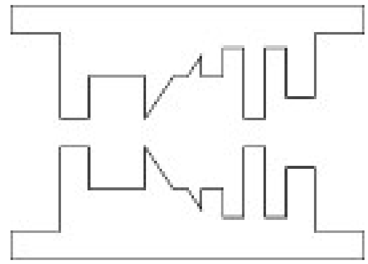

Figure 3. Example of a complex three-dimensional geometry requiring smooth internal diameter requested for fabrication using LIGA. This part is cylindrical in cross section.

This approach, and others like it, will allow a greater geometric variation and lower costs for LIGA products.

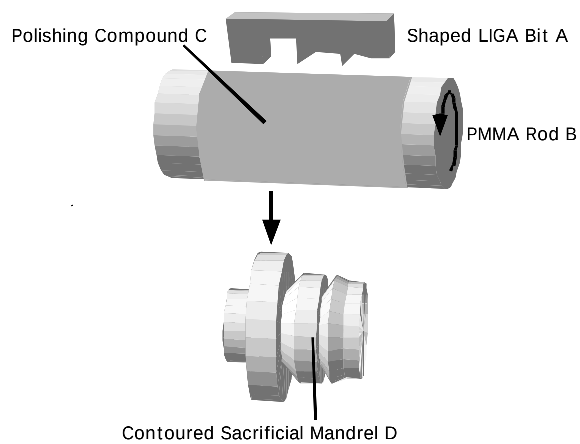

Figure 4. A schematic illustrating the contour polishing approach. A two dimensional LIGA tool is made and used with a rod of PMMA to form a smooth wall, three dimensional PMMA mandrel.

Summary:
There continues to be active LIGA R&D world wide, and introduction of LIGA products is slowly emerging in the commercial sector. Barriers to

commercialization include synchrotron access, specialized equipment availability, process and product reliability, and assembly and packaging. Progress is being made in all these areas, however the need for advancements is still apparent. Enough is currently known for specialized, LIGA-based, high value metal products or plastic replicates, to make it to the market. As R&D advances, the introduction of more products or perhaps even a pervasive introduction of LIGA products may emerge.

Sandia prototypes LIGA parts with commercial partners and has established baseline process know-how and custom equipment that can be licensed by commercial entities interested in LIGA production. Future research activities at Sandia will focus on producing cost-effective metal LIGA replicates, demonstrating fabrication of three dimensional microparts using LIGA tools, and examining reliability and packaging.

References:

1. E.W. Becker, W. Ehrfeld, P. Hagmann, A. Maner, D. Munchmeyer, "Fabrication of microstructures with high aspect ratios and great structural heights by synchrotron radiation lithography, galvanoformung and plastic moulding (LIGA process)," *Microelectron. Engng.* **4,** 35-36, 1986.
2. Spectrometer information can be obtained from the STEAG microParts GmbH web page at www.microparts.de.
3. Aspirator information can be obtained from the STEAG microParts GmbH web page at www.microparts.de.
4. "Miniature motors deliver big products," Design News, May 5, 1997.
5. J.M. Hruby, et al, "LIGA: Metals, Plastics, and Ceramics," Micromachining and Microfabrication Process Technology V, Proceedings of SPIE, September 2-22, 1999, Santa Clara, CA.
6. Jenoptik Mikrotechnik GmbH, Goschwitzer Strasse 40, D-07745 Jena, Germany, (+49 3641)65-3338, www.jo-mikrotechnik.com.
7. J. Gottert, H.O. Moser, F.J. Pantenburg, V. Saile, and R. Steininger, "ANKA- a synchrotron light source for x-ray based micromachining," *Microsystems Technologies*, Volume 6, Number 3, February 2000, pp. 113-116.
8. Information on CAMD can be found at http://camd.lsu.edu/.
9. Information on Aladdin can be found at http://www.src.wisc.edu.
10. S. K. Griffiths, A. Ting, and J.M. Hruby, "The influence of mask substrate thickness on exposure and development times for the LIGA process," *Microsystem Technologies*, Volume 6, Number 3, February 2000, pp. 99-102.
11. W. Ehrfeld, V. Hessel, H. Lowe, Ch. Schultz, L. Weber, "Materials of LIGA Technology," *Microsystem Technologies*, Volume 5, Number 3, February 1999, pp. 105-112.
12. J.T. Feddema, R. Simon, M. Polosky, T. Christenson, "Ultra-Precise Assembly of Micro-Electromechanical Systems (MEMS) Components," Sandia Report, SAND99-0746, April 1999.
13. M. Heckele, K.D. Muller, W. Bacher, "Hot embossing – The molding technique for plastic microstructures," *Microsystems Technologies*, Volume 4, Issue 3, pp. 122-124.
14. V. Piotter, T. Benzler, T. Hanemann, P. Norajitra, R. Ruprecht, J.H. Hausselt, "Molding technologies for innovative microfabrication," Micromachining and Microfabrication, Proceedings of SPIE, September 20-22,1999, Santa Clara, CA.

Acknowledgements:
The author gratefully acknowledges Stewart Griffiths for the calculations concerning areal throughput, and Alfredo Morales, Linda Domeier, and Michael Winter for the metal replication work, and Alfredo Morales for the contour polishing work. Acknowledgement also to the LIGA processing team at Sandia including Michelle Bankert, Doug Chinn, John Hachman, Craig Henderson, and Dawn Skala. Contributions to the Sandia effort were also made by Bill Bonivert and Dale Boehme of Axsun Technologies, and Steve Leith of Hewlett Packard while working at Sandia.

Sandia is a multiprogram laboratory operated by Sandia Corporation for the United States Department of Energy under contract DE-AC04-94AL85000.